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(54) Title: METHOD AND SYSTEM FOR DRIVING A SOLENOID

(57) Abstract: A system and method for a pulse width modulated (PWM) solenoid driver with a reduced rate of power consumption. The system for driving a solenoid includes a solenoid, a current set-point for establishing a desired current flow through the solenoid, and a step-down regulator circuit for controlling the current through the solenoid based on the difference between the desired current flow and the actual current flow through the solenoid. The step-down regulator circuit has a low internal resistance of not greater than approximately 1 ohm which contributes to the reduced rate of power consumption for the PWM solenoid driver.

METHOD AND SYSTEM FOR DRIVING A SOLENOID

TECHNICAL FIELD OF THE INVENTION

This invention relates generally to systems and methods for driving a solenoid and, more specifically, to systems and method for driving a solenoid that controls a valve in a mass flow controller (MFC).

BACKGROUND OF THE INVENTION

Many manufacturing processes require that the introduction rates of process gases into a process chamber be strictly controlled. These types of processes use mass flow controllers (MFCs) to control the flow rate of gases. An MFC may control the gas by implementing a solenoid driver circuit to control a valve. The flow rate into the chamber is proportional to the valve opening. In turn, the valve opening is proportional to a current flowing through a solenoid winding.

A basic circuit for a typical solenoid driver is shown in FIGURE 1. Solenoid driver 10 includes a voltage source 12, a control element 14 such as a transistor, and a load device, solenoid 16. The current through solenoid 16 is given by V_L/R_L, where V_L is the voltage across solenoid 16 as controlled by device 14, and R_L is the resistance of solenoid 16. R_L may vary as a result of operating temperature in solenoid 16. Solenoid driver 10 is continually controlled by means of changing a voltage across solenoid 16 through the use of control element 14. The impedance of solenoid 16 is both inductive and resistive. Typical inductance values range between 1H-4H, and corresponding resistance values range from 100Ω-300Ω. Supply voltage 12 used to drive the current in solenoid driver 10 may be in the range of 24 volts (±12 volts) to 36 volts(±18 volts). The voltage V_L applied across solenoid 16 is typically between 10 volts and 18 volts, depending on operating parameters such as

the desired valve opening and the pressure drop across the MFC device.

Unfortunately, there are two disadvantages with the typical solenoid driver 10 illustrated in FIGURE 1. The first disadvantage is that the force exerted by solenoid 16 is proportional to the current flowing through its windings and only indirectly proportional to the voltage across it. If the solenoid voltage is controlled, an additional time delay is introduced in the feedback loop and this delay may cause stability problems.

A second disadvantage of the circuit shown in FIGURE 1 is that power is often wasted in control element 14, especially when the difference between supply voltage 12 and the voltage V_L across solenoid 16 is large. Denoting supply voltage 12 as V_S and given V_S, V_L, and R_L, the dissipated power in control element 14 is equal to $(V_S - V_L) \times V_L/R_L$. The wasted power is dissipated as heat in control element 14. This dissipation is undesirable for two reasons. First, the dissipated power reduces the overall power budget of the system and may violate a power limit imposed by a customer on the MFC. Also, the heat generated through control element 14 may cause problems due to a lack of forced cooling such as a fan inside the unit.

Therefore, it is desirable for a solenoid driver to dissipate as little heat as possible so that the need for a cooling mechanism is reduced or eliminated. Also, it is desirable to reduce the energy consumption of the

control element in a solenoid driver so that the control element minimizes the demands placed on the overall power budget of the system.

SUMMARY OF THE INVENTION

The present invention provides a system and method for driving a solenoid that substantially eliminates or reduces disadvantages and problems associated with previously developed systems and methods for driving a solenoid.

More specifically, the present invention provides a system and method for a pulse width modulated (PWM) solenoid driver. The system for driving a solenoid includes a solenoid, a current set-point for establishing a desired current flow through the solenoid, and a step-down regulator circuit for controlling the current through the solenoid based on the difference between the desired current flow and the actual current flow through the solenoid.

The present invention provides an important technical advantage by reducing the amount of power wasted due to dissipation through a control element such as a transistor. The step-down regulator provides a minimal voltage drop due to the low resistance associated with it. Therefore, minimal power is dissipated through the internal resistance of the step-down regulator. This reduces the overall power budget needed to drive the solenoid and consequently reduces the cost associated with implementing the solenoid driver.

Another technical advantage of the present invention is that heat associated with the loss of energy through a control element such as a transistor used in a typical

solenoid driver is much reduced. Therefore, the necessity of forced cooling such as a fan inside the unit is eliminated.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention and the advantages thereof may be acquired by referring to the following description, taken in conjunction with the accompanying drawings in which like reference numbers indicate like features and wherein:

FIGURE 1 is a basic linear control circuit for a controller with a transistor as a control element;

FIGURE 2 is a basic circuit for a pulse width modulated solenoid current controller with the switch closed;

FIGURE 3 is a basic circuit for a pulse width modulated solenoid current controller with the switch open;

FIGURE 4 is a graphical representation of the peak-to-peak current in the solenoid of FIGUREs 2 and 3;

FIGURE 5 is a typical circuit for a 5 volts step-down regulator;

FIGURE 6 is one embodiment of the present invention for a PWM system for governing the current through a solenoid that controls a valve in a mass flow controller; and

FIGURE 7 is a table containing the component values for one embodiment of the circuit illustrated in FIGURE 6.

DETAILED DESCRIPTION OF THE INVENTION

Preferred embodiments of the present invention are illustrated in the FIGUREs, like numerals being used to refer to like and corresponding parts of various drawings.

The present invention provides a system and method for the application of a step-down regulator to solenoid power control. More specifically, the present invention provides a system for driving a solenoid. The system includes a solenoid, a current set-point for establishing a desired current flow through the solenoid, and a step-down regulator circuit for controlling the current through the solenoid based on the difference between the desired current flow and the actual current flow through the solenoid.

A basic circuit for Pulse Width Modulated (PWM) solenoid current controller 20 is shown in FIGURE 2 and FIGURE 3. In this circuit, a voltage source 22 is tied in series with an electronic switch 24 which can be controlled by a switch controller. Electronic switch 24 is tied in series with a load consisting of a solenoid 26 tied in parallel with diode 32. Solenoid 26 is represented as inductance 28 in series with resistance 30. FIGURE 2 represents the state of the circuit when electronic switch 24 is closed, while FIGURE 3 represents the state of the circuit when electronic switch 24 is open. When electronic switch 24 is closed, as in FIGURE 2, current builds up on the load represented by

the resistance 30 and the inductance 28 of solenoid 26. The current built up in this "on" period is stored in inductance 28. When electronic switch 24 is open, as shown in FIGURE 3, the stored current in the inductance 28 decays due to the reverse voltage drop caused by the resistance 30 and the voltage drop across diode 32. The equivalent steady-state drive voltage V_{SSD} applied across solenoid 26 through implementing this switched power source is $V_{SSD}=V*[t_{on}/(t_{on}+t_{off})]$, where V is voltage source 22, t_{on} is the length of time the switch is closed and t_{off} is the length of time the switch is open.

FIGURE 4 is a graphical representation of the peak-to-peak current in solenoid 26 during the opening and closing of electronic switch 24. The peak-to-peak current i(t) depends on inductance 28 and resistance 30 and the period of the PWM signal, $(t_{on}+t_{off})$. Current control can be achieved if the on/off periods of electronic switch 24 are controlled appropriately to maintain the desired current level i(t) in solenoid 26. The ratio $[t_{on}/(t_{on}+t_{off})]$ is called the duty cycle. At the instant that electronic switch 24 is closed, the current i(t) in solenoid 26 begins to increase from its initial value i_1 to its final value i_2 at which point electronic switch 24 is opened. This increase is not instantaneous due to the fact that the current through an inductor cannot change instantaneously. Instead, an exponential curve is seen between the closing of electronic switch 24 and the opening of electronic switch 24. Likewise, when

electronic switch 24 is opened, the current i(t) in inductance 28 begins to decay exponentially from the initial value of i_2 to the final value of i_1 when electronic switch 24 is closed again. This process repeats itself as timed by the opening and closing of electronic switch 24. The average value i_{AV} for the current through solenoid 26 is approximately equal to $[(i_1+i_2)/2]$.

FIGURE 5 is a 5-volt step-down switching regulator 34. The heart of this circuit is step-down regulator integrated circuit 36 (buck switching regulator). Step-down regulator integrated circuit 36 may be a commercially-available, low-cost precision integrated circuit generally used in 5-volt (3.3-volt or 2.7-volt, etc.) switching power supply controls. In FIGURE 5, step-down regulator integrated circuit 36 is represented as LM2674, which is a product of the National Semiconductor Corporation of Santa Clara, California. This particular step-down regulator integrated circuit 36 has an internally controlled frequency of 260 kHz, PWM control, and feedback compensation and a low internal resistance of approximately 0.25 ohms. The present invention is not limited to the LM2674 device. Many step-down regulators exist on the market and can be used in the present invention as well. Typical ranges for internal resistances of step-down regulators on the market range from approximately 0.1 to 1 ohm.

Step-down regulator integrated circuit 36 is normally referenced to ground 38 and generates 5-volt output 40 across storage capacitor 50. 5-volt output 40 is maintained by switching a suitably-sized inductor 42 between positive switching voltage supply 44 and 5-volt output 40 during the "on" period and between ground 38 and 5-volt output 40 during the "off" period. When inductor 42 is tied between positive switching voltage 44 and 5-volt output 40, positive switching voltage 44 is tied to input voltage 43 (8 volts or greater) through the switching device within step-down controller 36.

The switching voltage supply 44 of inductor 42 is also connected to a cathode of diode 46. The anode of diode 46 is grounded to provide a current path in the "off" period. Storage capacitor 50 is connected between 5-volt output 40 and ground 38. Load 52, requiring a 5-volt supply voltage, is connected in parallel with storage capacitor 50. When step-down regulator integrated circuit 36 is first turned on with switch 48 opened, 5-volt output 40 across storage capacitor 50 is zero (the voltage across a capacitor cannot change instantaneously). Therefore, the full switching voltage supply 44 is applied to inductor 42 for the maximum pulse width within the PWM period. Inductor current 54 begins to flow through inductor 42 and can be maintained through diode 46 even when the power is removed from inductor 42 during the "off" portion of the control cycle. Inductor current 54 will be built up during subsequent on/off

cycles until equilibrium is established between inductor current 54 and load current 56.

In the steady-state operating mode for the circuit in FIGURE 5, 5-volt output 40 across storage capacitor 50 is precisely regulated by the control circuits inside step-down regulator integrated circuit 36. Should load current 56 increase or decrease from the steady-state level, feedback control V_{FB} will cause step-down regulator integrated circuit 36 to respectively increase or decrease the duty cycle $[t_{on}/(t_{on}+t_{off})]$ of switching voltage supply 44 so that 5-volt output 40 across load 52 is maintained. Similarly, if 5-volt output 40 increases or decreases, the pulse width of the switching voltage supply 44 is respectively decreased or increased to maintain 5 volts across load 52.

One embodiment of the present invention is shown in FIGURE 6. This circuit incorporates the use of step-down regulator integrated circuit 60 for current control in solenoid 62. The step-down regulator may include an input voltage pin, a feedback voltage pin, a reset pin, a ground pin, and a switching voltage pin. Solenoid 62 may control a valve in a mass flow controller (MFC). Step-down regulator integrated circuit 60 is supplied from positive voltage supply 64 and negative voltage supply 66. The voltage lines for positive supply voltage 64 and negative supply voltage 66 are filtered with capacitor pairs C_1,C_2, and C_6,C_7. Filtering can protect the supply lines and any other circuitry connected to the supply

lines from transients created by the switching action of step-down regulator integrated circuit 60. The ranges for positive supply voltage 64 and negative supply voltage 66 can be respectively ($^+$12 volts - $^+$18 volts) and ($^-$12 volts - $^-$18 volts) with respect to ground 68.

Solenoid 62 is connected between switching voltage 70 of step-down regulator integrated circuit 60 and negative supply voltage 66 through current-sensing resistor R_{26}. Diode D_1 is also connected between switching voltage 70 of step-down regulator integrated circuit 60 and negative supply voltage 66. The small voltage drop (typically a few hundred mV at full solenoid current) across current-sensing resistor R_{26} may be amplified by operational amplifier 72 and supporting components (R_{17-25}, C_{8-10}) to generate voltage analog 74 of solenoid current 76. Operational amplifier 72 can be connected as a differential amplifier with inputs referenced to ground 68. Therefore, using component values listed in FIGURE 7, at 0 mA current, voltage analog 74 of solenoid current 76 is 0v, and at 110 mA voltage analog 74 of solenoid current 76 is 5 volts.

Step-down regulator integrated circuit 60 requires that feedback voltage 104 is 5 volts above the potential of regulator ground 78 when solenoid current 76 through solenoid 62 matches a desired solenoid current required to activate the valve in the MFC. Regulator ground 78, however, is tied to negative supply voltage 66. Voltage analog 74, therefore, must be shifted negatively by

$-V_2+5$ volts, where $-V_2$ is negative supply voltage 66 . This task can be performed by operational amplifier 80 and its supporting components (R_{8-13}). Assuming that the value of R_{12} is negligible compared to R_{11} and using the values of resistance specified in FIGURE 7 for R_{8-13}, plus node voltage 82 of operational amplifier 80 is equal to:

$$(2.5+V_2)\frac{R_{11}}{(R_{11}+R_{10})}-V_2=\frac{(5-V_2)}{3} \qquad \text{[EQN 1]}$$

In the linear operating mode, minus node voltage 84 of operational amplifier 80 must match that of plus node voltage 82 of operational amplifier 80 within a negligible offset voltage. Therefore, those voltages will be equal only if,

$$\frac{(5-V_2)}{3}=V_B\frac{R_8}{R_8+R_9} \qquad \text{[EQN 2]}$$

where V_B is bias voltage 86, the output voltage of operational amplifier 80. Thus, solving for bias voltage 86 with the indicated component values specified in FIGURE 7 yields,

$$V_B=5-V_2 \qquad \text{[EQN 3]}$$

Flow set-point voltage 88 is input to operational amplifier 90 and corresponding components (R_1, R_2, C_4, C_5). Flow set-point voltage 88 may be established by a digital signal processor which is part of a MFC. The digital

signal processor may include software that compares the value of the flow rate through the valve of the MFC with the desired flow rate. The software then may generate a valve set-point voltage 88. The valve set-point voltage 88 is used to create a set-point voltage 92 that is used to generate feedback voltage 104. Set-point voltage 92 is compared to a proportionally scaled and shifted voltage analog 74. The difference between set-point voltage 92 and voltage analog 74 is used by the step-down regulator integrated circuit 60 to determine the pulse width of switching voltage 70 which, in turn, controls solenoid current 76.

Valve set-point voltage 88 is connected to operational amplifier 90 and supporting components R_{1-2}, C_{4-5} to form active lowpass filter 94. Active lowpass filter 94 may have a -3dB attenuation at 59.2Hz and a 0.686 damping coefficient (approximate Butterworth lowpass filter response) with component values in FIGURE 7. Note that a Butterworth filter response is not required here. This could have been accomplished with other filters such as a Chebyshev or a Bessel filter, yet a Butterworth filter provides a flat frequency response with moderate time domain overshoot. Valve set-point voltage 88 can be either a steady DC level between 0 and 5 volts or a pulse width modulated signal at 610 (or greater) pulses per second (pps). Active lowpass filter 94 can reduce the fundamental or 610 Hz component by a factor of 100, the second harmonic by a factor of 200, and so on. Thus, the

output of active lowpass filter 94 is set-point voltage 92 which may either be a DC set-point voltage or an average PWM set-point voltage, both ranging from 0 volts to 5 volts.

Set-point voltage 92, the voltage analog 74, and the bias voltage 86 are combined in a differential amplifier stage 96. Using the component values as specified in FIGURE 7, plus node voltage 98 of operational amplifier 100 is given by,

$$[V(i)-(5-V_2)]\frac{R_{13}}{R_{13}+R_{14}}+5-V_2=V(i)+\frac{5-V_2}{2}, \qquad \text{[EQN 4]}$$

where V(i) represents voltage analog 74 of solenoid current 76. Using the component values in FIGURE 7, the voltage at minus node 102 of operational amplifier 100 is given by,

$$(V_{sp}-V_{FB})\frac{R_4}{R_3+R_4}+V_{FB}=\frac{V_{sp}+V_{FB}}{2}, \qquad \text{[EQN 5]}$$

where V_{SP} is set-point voltage 92 and V_{FB} is feedback voltage 102. Setting equation 4 equal to equation 5 yields,

$$V_{FB}=V(i)-V_{sp}+(5-V_2). \qquad \text{[EQN 6]}$$

The output of operational amplifier 100, V_{FB}, is feedback voltage 102 consisting of the difference between voltage analog 74 and set-point voltage 92. Feedback voltage 74

is biased 5 volts above negative supply voltage 66 ($-V_2$), satisfying the operational needs of step-down regulator integrated circuit 60.

In the event of an initialization process of the digital signal processor of an MFC, it may be desirable to disable the PWM solenoid driver shown in FIGURE 6 until the initialization is complete. Also in the event of an emergency shut-off or maintenance it may also be necessary to disable the PWM solenoid driver. In either case, transistor Q1 and transistor Q2, in conjunction with resistive components R_{5-7}, R_{12}, R_{15-16} and diodes D1 and D2, can provide a means to disable the PWM solenoid driver circuit illustrated in FIGURE 6.

Reset node 106 or OFF node 108 can be driven to near ground level so that transistor Q1 turns on and its collector is pulled to 5 volts. The collector of transistor Q1 is tied to the base of transistor Q2 through R15. Biasing the base of transistor Q2 this way can cause transistor Q2 to turn on. In turn, ON/$\overline{\text{OFF}}$ pin 110 of step-down regulator integrated circuit 60 can be pulled to negative supply 66 and step-down regulator integrated circuit 60 can be turned off. If reset node 106 or OFF node 108 is not pulled low (i.e. tied to +5V or left floating), then both transistor Q1 and transistor Q2 can be disabled, ON/$\overline{\text{OFF}}$ pin 110 remains disconnected from negative supply voltage 66, and step-down regulator integrated circuit 60 remains on. Resistor R_{12} can be used to bias output 86 of operational

amplifier 80 slightly positive in order to ensure that step-down regulator integrated circuit 60 is shut off when set-point voltage 92 is 0 volts.

The present invention may be used to drive a valve in a mass flow controller. The mass flow controller may include a flow sensor with interface circuitry, sensor linearization, derivative control, proportional control, and a closed loop control algorithm. Reference is made to the flow sensor interface circuitry disclosed in U.S. Patent Application Serial No. 09/350,746 filed July 9, 1999 by T.I. Pattantyus et. al. entitled "Improved Mass Flow Sensor Interface Circuit". In addition, reference is made to the linearization method disclosed in U.S. Patent Application Serial No.09/350,747 filed July 9, 1999, by T.I. Pattantyus and F. Tariq entitled "Method and System for Sensor Response Linearization". Reference is also made to the derivative control method disclosed in U.S. Patent Application Serial No. 09/351,120 filed on July 9, 1999, by E. Vyers, *et al.*, entitled "A System and Method For A Digital Mass Flow Controller". Additionally, reference is made to the proportional control method disclosed in U.S. Patent Application Serial No. 09/351,098 filed on July 9, 1999, to E. Vyers, entitled "System and Method for a Variable Gain Proportional-Integral (PI) Controller." Lastly, reference is made to the advanced digital control algorithm disclosed in U.S. Patent Application Serial No. 09/350,744 filed on July 9, 1999 by K. Tinsley entitled "System and Method of

Operation of a Digital Mass Flow Controller". It is important to note that the present invention is not limited to use in a mass flow controller including the above components.

There are many sources, data sheets, application reports giving detailed descriptions of step-down regulators. Reference is made here to the National Semiconductor Data Sheet titled "LM2674 SIMPLE SWITCHER® Power Converter High Efficiency 500mA Step-Down Voltage Regulator," September, 1998. It is important to note that use is not limited to the National Semiconductor device. Other regulator ICs may be used as well.

A technical advantage of the circuit is that little power is wasted in step-down regulator integrated circuit 60. The amount of power dissipated by the solenoid driver illustrated in FIGURE 6 depends on all of the components including solenoid 62, diode D1, positive supply voltage 64, negative supply voltage 66, and step-down regulator integrated circuit 60. Little power is dissipated by step-down regulator integrated circuit 60 when step-down regulator integrated circuit 60 is on because the voltage drop across step-down regulator integrated circuit 60 is minimized by careful design. The careful design enables a low internal resistance in step-down regulator integrated circuit 60 (~0.1 - ~1.0 ohm). The voltage across diode D1 during the "off" cycle (when the switch internal to step-down regulator integrated circuit 60 is open) is also small, especially if a

Schottky diode is used. Consequently, most of the power dissipated in the circuit of FIGURE 6 is spent on maintaining solenoid current 76. Due to the low internal resistance of step-down regulator integrated circuit 60, step-down regulator can have a reduced rate of power consumption compared to the power consumed by prior art control elements. Consequently, the solenoid driver circuit may have a lower rate of power consumption than prior art methods.

Another technical advantage of the present invention is that voltage analog 74 is used to serve two purposes. The first purpose is that it can be used as an indication to the user that the MFC is operating properly. Second, it is used as a dynamic feedback signal which is compared to set-point voltage 92 (a function of valve set-point voltage 88) to determine feedback voltage 104 of step-down regulator integrated circuit 60. Feedback voltage 104 controls the duty cycle of switching voltage 70 across solenoid 62 and, in turn, controls solenoid current 76.

An additional advantage provided by most of the commercial step-down regulator integrated circuits is the built-in short circuit protection. If solenoid 62 is short circuited, the output current of step-down regulator integrated circuit 60 will exceed the maximum allowable limit which causes the switching voltage 30 to be turned off almost instantaneously. The circuit in

FIGURE 6 can be run with a shorted output indefinitely without any damage to any part of the circuit.

Although the present invention has been described in detail herein with reference to the illustrative embodiments, it should be understood that the description is by way of example only and is not to be construed in a limiting sense. It is to be further understood, therefore, that numerous changes in the details of the embodiments of this invention and additional embodiments of this invention will be apparent to, and may be made by, persons of ordinary skill in the art having reference to this description. It is contemplated that all such changes and additional embodiments are within the spirit and true scope of this invention as claimed below.

WHAT IS CLAIMED IS:

1. A pulse width modulated solenoid driver with a reduced rate of power consumption comprising:

a solenoid;

a flow set-point voltage for establishing a desired current flow through said solenoid; and

a step-down regulator circuit for controlling said actual current flow through said solenoid based on a difference between said desired current and said actual current flow through said solenoid.

2. The pulse width modulated solenoid driver of Claim 1, wherein said step-down regulator has a low internal resistance of not greater than approximately 1 ohm.

3. The pulse width modulated solenoid driver of Claim 2, wherein said low internal resistance contributes to said reduced rate of power consumption of said pulse width modulated solenoid driver.

4. The pulse width modulated solenoid driver of Claim 1, wherein said step-down regulator comprises an input voltage pin, a feedback voltage pin, a reset pin, a ground pin, and a switching voltage pin.

5. The pulse width modulated solenoid driver of Claim 4, further comprising:

a first supply voltage tied to said input voltage pin of said step-down regulator;

a first terminal of said solenoid tied to said switching voltage pin;

a second terminal of said solenoid tied in series to a current-sensing resistor which is also tied to a second supply voltage;

a cathode of a diode tied to said switching voltage pin;

an anode of said diode tied to a third supply voltage; and

said ground pin of said step-down regulator tied to said third supply voltage.

6. The pulse width modulated solenoid driver of Claim 5, wherein said diode is a Schottky diode.

7. The pulse width modulated solenoid driver of Claim 5, further comprising a first amplifier stage for filtering and amplifying a voltage across said current-sensing resistor to generate a voltage analog of said actual current flow through said solenoid.

8. The pulse width modulated solenoid driver of Claim 7, wherein said voltage analog is used as a diagnostic tool to monitor a performance of said pulse width modulated solenoid driver.

9. The pulse width modulated solenoid driver of Claim 7, wherein said amplifier stage comprises an operational amplifier, resistive components, and capacitive components.

10. The pulse width modulated solenoid driver of Claim 7, wherein said feedback voltage pin is biased at a step-down regulator operationally determined voltage above said ground pin voltage when said actual current flow through said solenoid matches said desired current flow.

11. The pulse width modulated solenoid driver of Claim 10, further comprising a second amplifier stage for negatively shifting said voltage analog of said actual current flow through said solenoid by a sum of said second supply voltage and said step-down regulator operationally determined voltage to generate a scaled and biased voltage analog of said actual current flow.

12. The pulse width modulated solenoid driver of Claim 11, wherein said second amplifier stage comprises an operational amplifier and resistive components, said second amplifier stage is a times-two, non-inverting amplifier.

13. The pulse width modulated solenoid driver of Claim 11, further comprising a third amplifier stage for

filtering said flow set-point voltage to generate a set-point voltage.

14. The pulse width modulated solenoid driver of Claim 13, wherein said third amplifier stage is a low-pass filter comprising an operational amplifier and resistive and capacitive components, said resistive and capacitive components determining a cut-off frequency of said low-pass filter.

15. The pulse width modulated solenoid driver of Claim 13, further comprising a fourth amplifier stage for comparing said scaled and biased voltage analog of said actual current flow and said set-point voltage to generate a feedback voltage for said feedback voltage pin on said step-down regulator, said step-down regulator generating a duty cycle for a switching voltage at said switching pin in response to said feedback voltage.

16. The pulse width modulated solenoid driver of Claim 15, wherein said fourth amplifier stage comprises an operational amplifier and resistive components.

17. The pulse width modulated solenoid driver of Claim 15, wherein said solenoid controls a valve in a mass flow controller.

18. The pulse width modulated solenoid driver of Claim 17, wherein said flow set-point voltage is determined by a digital signal processor in said mass flow controller.

19. The pulse width modulated solenoid driver of Claim 18, wherein said digital signal processor compares an actual flow through said valve and calculates said flow set-point voltage based on a desired flow through said valve, said desired flow through said valve is a function of said desired current flow.

20. The pulse width modulated solenoid driver of Claim 19, further comprising circuitry to generate a reset signal connected to said reset pin on said step-down regulator.

21. A method for driving a solenoid in a pulse width modulated solenoid driver with a reduced rate of power consumption, said method comprising:

generating an actual current flow through said solenoid using a pulse width modulated signal output from a step-down regulator;

converting said actual current flow through said solenoid to a voltage analog of said actual current flow through said solenoid;

generating an error signal that is a function of a set-point voltage and said voltage analog of said actual current flow through said solenoid, said set-point voltage is a function of a desired current flow through said solenoid; and

feeding back said error signal to said step-down regulator to alter a pulse width of said pulse width modulated signal.

22. The method of Claim 21, wherein said step-down regulator has a low internal resistance of not greater than approximately 1 ohm.

23. The method of Claim 22, wherein said low internal resistance contributes to said reduced rate of power consumption of said pulse width modulated solenoid driver.

24. The method of Claim 21, wherein said step-down regulator comprises an input voltage pin, a feedback voltage pin, a reset pin, a ground pin, and a switching voltage pin.

25. The method of Claim 24, wherein the steps of generating said actual current flow through said solenoid further comprises:

connecting a first supply voltage to said input voltage pin of said step-down regulator;

connecting a first terminal of said solenoid to said switching voltage pin;

connecting a second terminal of said solenoid to a first terminal of a current-sensing resistor;

connecting a second terminal of said current-sensing resistor to a second supply voltage;

connecting a cathode of a diode to said switching voltage pin;

connecting an anode of said diode to a third supply voltage; and

connecting said ground pin of said step-down regulator to said third supply voltage.

26. The method of Claim 25, wherein said diode is a Schottky diode.

27. The method of Claim 25, wherein the step of converting said actual current flow through said solenoid

further comprises the step of amplifying and filtering with a first amplifier stage a voltage across said current-sensing resistor to generate said voltage analog of said actual current flow through said solenoid.

28. The method of Claim 27, further comprising using said voltage analog to monitor a performance of said pulse width modulated solenoid driver.

29. The method of Claim 27, wherein said amplifier stage comprises an operational amplifier, resistive, and capacitive components.

30. The method of Claim 27, wherein said feedback voltage pin is biased at a step-down regulator operationally determined voltage above said ground pin voltage when said actual current flow through said solenoid matches said desired current flow.

31. The method of Claim 30, wherein the step of generating an error signal further comprises negatively shifting with a second amplifier stage said voltage analog of said actual current flow through said solenoid by the sum of said second supply voltage and said step-down regulator operationally determined voltage to generate a scaled and biased voltage analog of said actual current flow

32. The method of Claim 31, wherein said second amplifier stage comprises an operational amplifier and resistive components, said second amplifier stage is a times-two, non-inverting amplifier.

33. The method of Claim 31, wherein the step of generating said error signal further comprises filtering said flow set-point voltage with a third amplifier stage to generate said set-point voltage.

34. The method of Claim 33, wherein said third amplifier stage is a low-pass filter comprising an operational amplifier and resistive and capacitive components, said resistive and capacitive components determining a cut-off frequency of said low-pass filter.

35. The method of Claim 33, wherein the step of generating said error signal further comprises comparing said scaled and biased voltage analog of said actual current flow through said solenoid with said set-point voltage to generate a feedback voltage for said feedback voltage pin on said step-down regulator using a fourth amplifier stage.

36. The method of Claim 35, wherein said fourth amplifier stage comprises an operational amplifier and resistive components.

37. The method of Claim 35, wherein said solenoid controls a valve in a mass flow controller.

38. The method of Claim 37, wherein said flow set-point voltage is determined by a digital signal processor in said mass flow controller.

39. The method of Claim 38, wherein said digital signal processor compares an actual flow through said valve and calculates said flow set-point voltage based on a desired flow through said valve, said desired flow through said valve is a function of said desired current flow.

40. A pulse width modulated solenoid driver with a reduced rate of power consumption for driving a valve in a mass flow controller, said pulse width modulated solenoid driver comprising:

a solenoid;

a flow set-point voltage for establishing a desired current flow through said solenoid;

a voltage analog of an actual current flow through said solenoid to be used as a diagnostic tool to monitor a performance of said pulse width modulated solenoid driver; and

a step-down regulator using a function of said flow set-point voltage and said voltage analog to control an actual current flow through said solenoid, said step-down regulator having a low internal resistance of not greater than approximately 1 ohm that contributes to said reduced rate of power consumption.

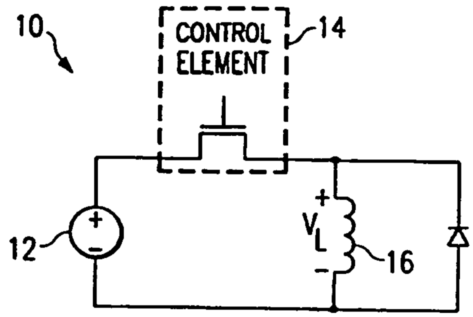

FIG. 1
(PRIOR ART)

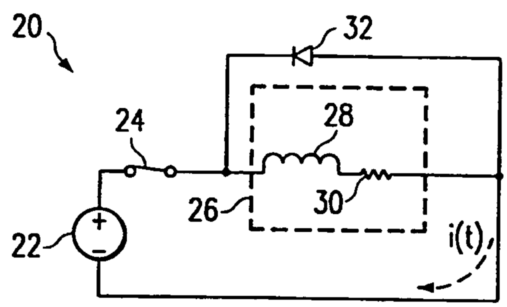

FIG. 2

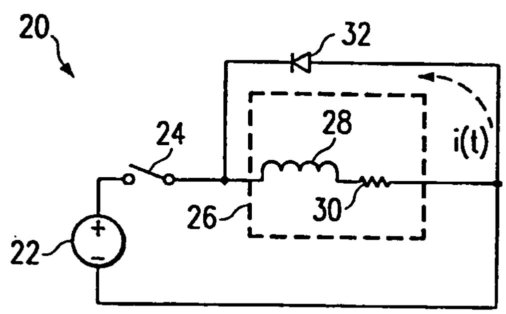

FIG. 3

ELEMENT	VALUE
R1	392k
R2	392k
R3	100k
R4	100k
R5	47kΩ
R6	100kΩ
R7	10kΩ
R8	50kΩ
R9	100kΩ
R10	50kΩ
R11	100kΩ
R12	2.2kΩ
R13	100kΩ
R16	100kΩ
R15	47kΩ
R16	100kΩ
R17	100kΩ
R18	9.09kΩ
R19	100kΩ
R20	9.09kΩ
R21	10kΩ
R22	100kΩ
R23	100kΩ
R24	100kΩ
R25	9.09kΩ
C1	47μF
C2	0.1μF
C3	10000pF
C4	10000pF
C5	4700pF
C6	47μF
C7	0.1μF
C8	10000pF
C9	10000pF
C10	10000pF
OP-AMPS (72, 80, 90, 100)	TLΦ64

FIG. 7

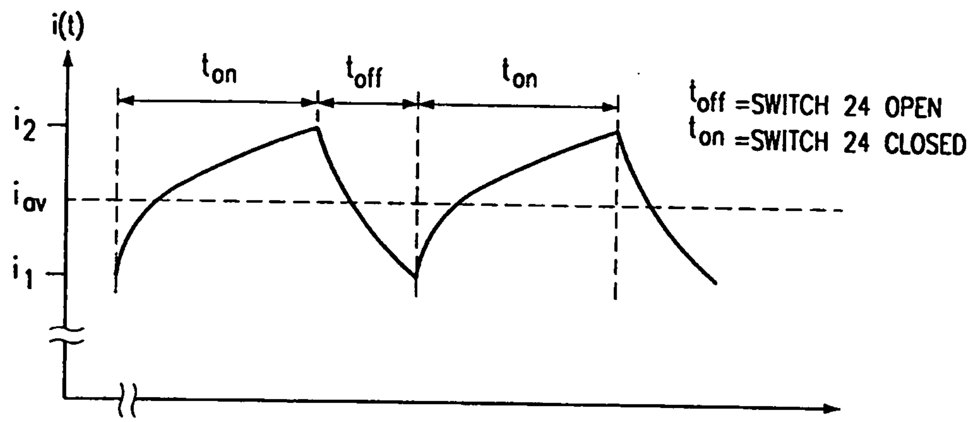
i(t)
t_{on}
t_{off}
t_{on}
i_2
i_{av}
i_1
t_{off} =SWITCH 24 OPEN
t_{on} =SWITCH 24 CLOSED

FIG. 4

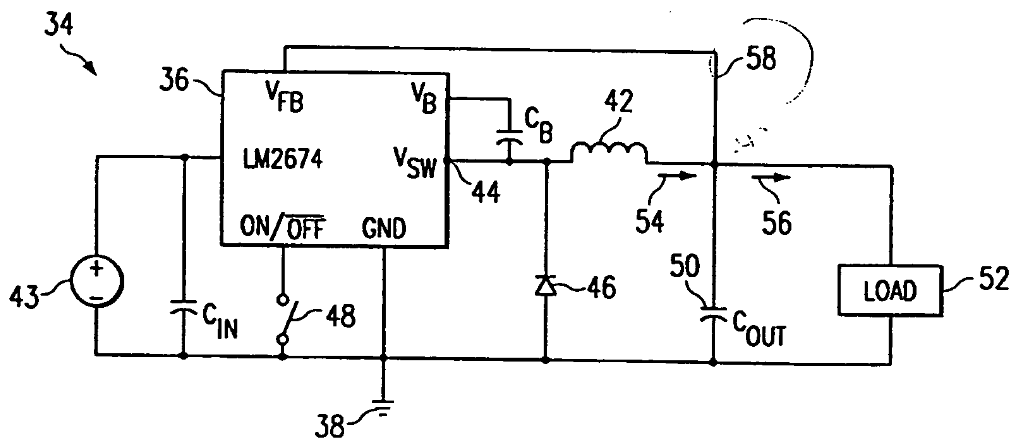
34
36
V_{FB}
V_B
LM2674
V_{SW}
ON/$\overline{OFF}$
GND
C_B
42
58
44
54
56
43
C_{IN}
48
46
50
C_{OUT}
LOAD
52
38

FIG. 5

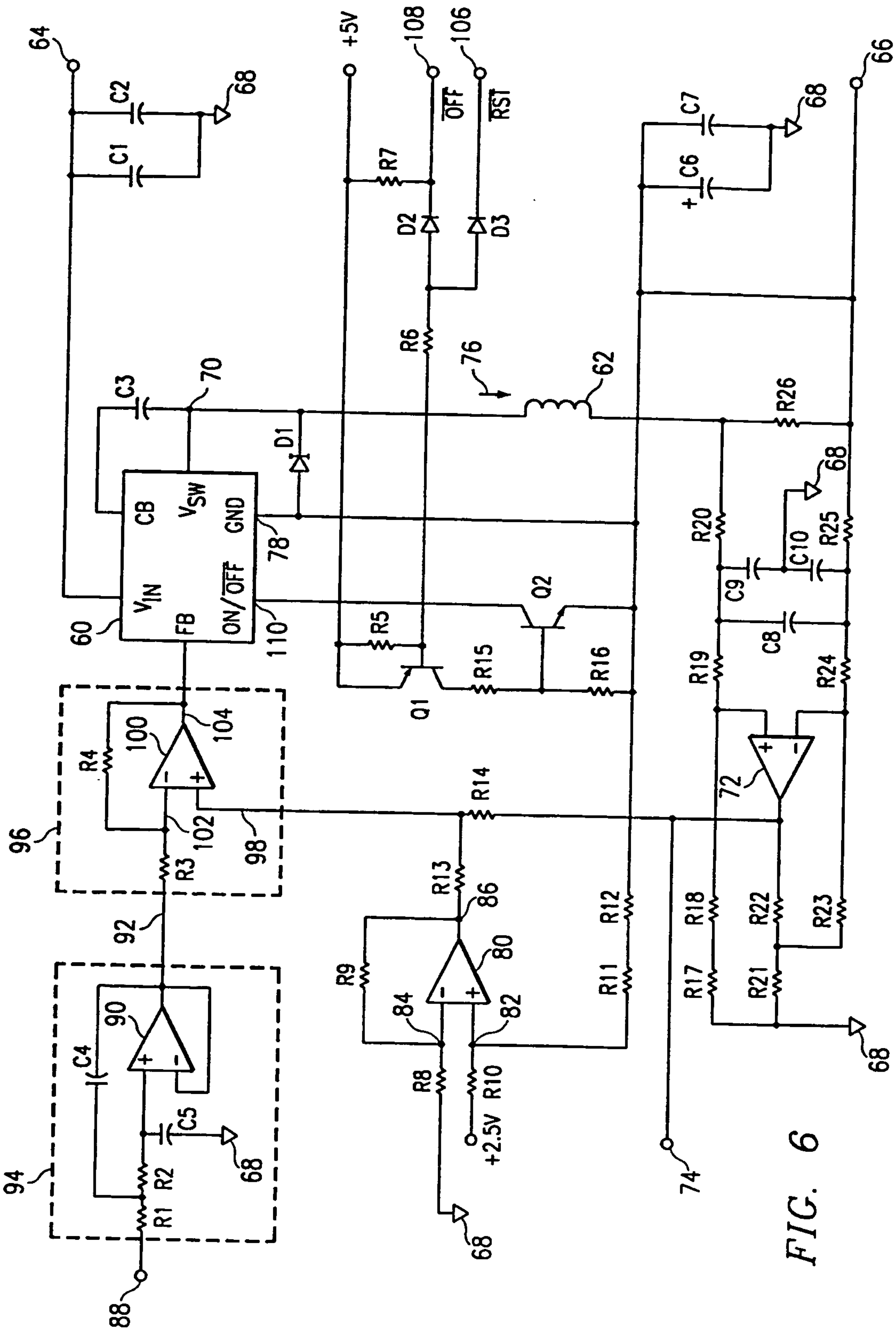
64
C2
C1
68
+5V
108
106
OFF
RST
R7
D2
D3
C7
C6
66
R6
76
62
C3
70
D1
CB
VSW
GND
VIN
FB
ON/OFF
60
78
110
R26
R20
R25
C10
C9
C8
Q2
R5
Q1
R15
R16
R19
R24
R4
100
104
96
102
R3
98
R14
72
92
R13
86
R12
R18
R22
R23
90
C4
R9
84
80
R11
R17
R21
82
C5
R8
R10
+2.5V
94
R2
R1
74
88

FIG. 6

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/40274

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01H47/32 H02M3/156

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01H H02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, PAJ, EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	US 5 835 330 A (KIRSCHNER MICHAEL ET AL) 10 November 1998 (1998-11-10) column 2, line 46 -column 3, line 35; figures 1,2	1-6, 21-26,40
A	EP 0 393 847 A (DELCO ELECTRONICS CORP) 24 October 1990 (1990-10-24) abstract	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 November 2000	07/12/2000
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Salm, R

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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PCT/US 00/40274

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